Research on a Counter-Rotating Propeller-Type Tidal Stream Power Unit with Winglets at Rear Blades

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Abstract

Tidal stream is expected as a high-integrity energy source in the world. Tidal current energy extraction devices can be categorized as a horizontal axis system and a vertical axis system. The authors have developed a horizontal axis counter-rotating type power unit which is applied in the conversion of wind energy and tidal energy. A counter-rotating tidal stream power unit is composed of tandem propellers driving double rotational armatures, while the rotating torques are counter-balanced in the power unit. The power unit can be moored with one cable and keep the posture stable without rolling motion in the tidal stream, in which the cable is hooked at the balancing point of the moment among the buoyancy, gravity and drag. The posture, however, may lose balance by a dynamic disturbance. To keep the posture stable in every circumstance, the winglets were installed on the rear blades. In this research, effectiveness of winglets in case mooring with a wire near the water surface was verified by the circulation type water channel tests. Besides, the blade performance was analyzed by the CFD. As the result, it is noticed that the high blade load can be achieved at near the blade tip by setting the winglets.

Keywords : Tidal Stream, Power Unit, Counter-Rotating, Tandem Propellers, CFD

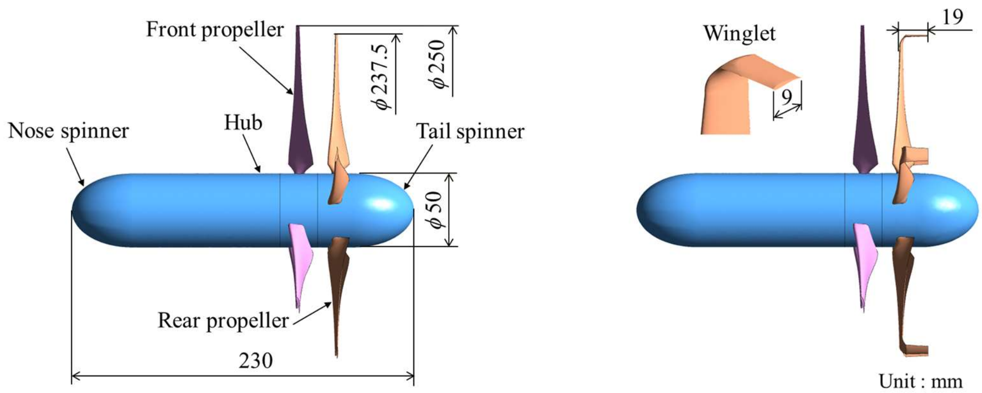
1. Introduction

The tidal current is expected as an attractive renewable energy source because the time change of flow direction and velocity is predictable. Tidal current energy extraction devices can be categorized as a horizontal axis system (Ordonez-Sanchez et al., 2019) and a vertical axis system (Grondeau et al., 2019). The authors have developed a horizontal axis counter-rotating type power unit which is applied in the conversion of wind energy (Kubo and Kanemoto, 2008) and tidal energy (Funami et al., 2017). This type of power unit is composed of the tandem propellers driving double rotational armatures, in which the rotating torques are counter balanced. The performance of the power unit has been validated in the previous works (Huang et al., 2016). In addition, the offshore test has also verified at Nagasaki Bay, Japan that it not only can get the excellent power generation but also can guarantee the safety operation (Samura et al., 2019).

In this research, a mooring support structure is applied to the horizontal axis counter-rotating type power unit, which is not only save the initial cost due to the civil construction but also appropriate for using at narrow strait due to set up easily. The counter-rotating type power unit can keep the posture stable without rolling motion in the stream when it is mooring with a cable at moment center among the buoyancy, the gravity, and the drag force. In such an arrangement, the drag force induced from downstream type propellers works effectively to keep the horizontal posture. However, once the unit inclines against the mainstream by unexpected change of local flow velocity, the horizontal posture is disrupted and further aggravated by the drag force induced from the flow separation around the casing which includes a nacelle supporting a generator and two hubs of the front and rear propellers. Therefore, the winglet used in aircraft is set to the blade tip of the rear propeller to help the power unit recover to horizontal posture. In this paper, effectiveness of winglets in case mooring with a wire near the water surface was verified by the circulation type water channel tests. Besides, the blade performance was analyzed by the CFD. As the result, it is noticed that the high blade load can be achieved at near the blade tip by setting the winglets.

2. Circulation type water channel tests

Figure 1 shows the model power units with and without winglets at rear propeller. The front and rear propeller blades were designed based on Blade Element Momentum Theory. The upstream side of model including nose spinner does not rotate and the tail spinner rotates together with the rear propeller. The generator is not installed in the models. The power unit consists of front propeller with three blades and rear propeller with five blades. The unit is set in a circulation type water channel with a cross-sectional area of 0.7 m (water depth) x 1.0 m (width) and moored with a wire at the nose spinner. In the experiments, the posture of the model was analyzed with the images by a camera. Besides, the rotational speeds of front and rear propeller were measured using a stroboscope (SATOTECH DT-2349JP). In the following discussion, the power unit model with winglet is called as PU_W in comparison with PU_O of the model without the winglet. The flow velocity V_{in} was changed from 0.7 m/s to 0.8 m/s, 0.9 m/s and 1.0 m/s.



Case without winglet　　Case with winglets

Fig. 1 Models with and without winglet.

Figure 2 shows the tilt angle θ of the experimental result and Fig. 3 is the counter-rotational speed N_t. The abscissa V_{in} is the flow velocity. As shown in Fig. 2, the θ in case PU_W was about 8 degrees lower than the case PU_O regardless of the flow velocity. Besides, in case PU_W, the counter-rotational speed N_t became 1.3 times higher than the case PU_O because of the low tilt angle as shown in Fig. 2.

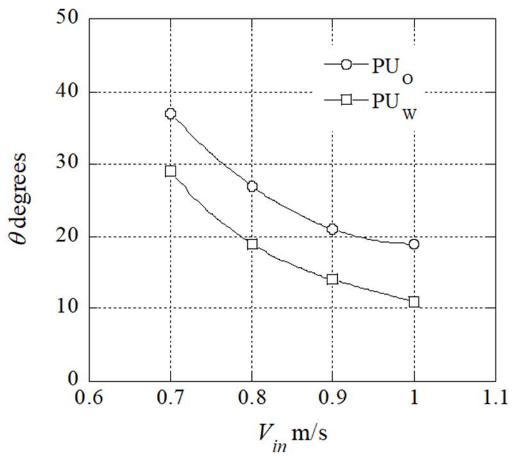


Fig. 2 Changes in tilt angle due to flow velocity.

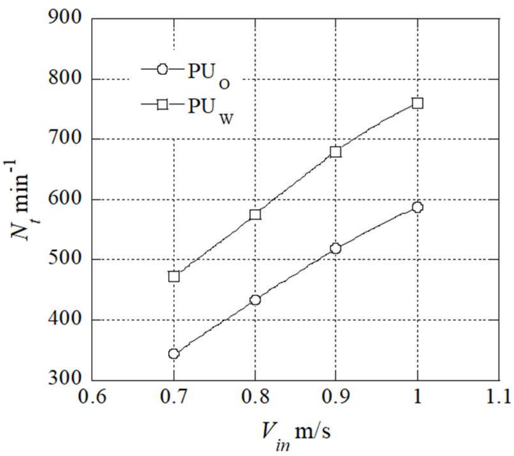


Fig. 3 Changes in counter-rotational speed.

3. Numerical simulations

The 3-D turbulent flow was simulated at the steady state condition by the commercial CFD code of ANSYS-CFX ver.19 with SST turbulent model to understand the propeller performances with and without winglet. The simulation domain is composed of 1 pitch passage areas of front and rear propellers. Besides, the condition that the tangential averaged parameters are transferred was adopted at the interface between front and rear propellers. The number of the grids for the model PU_O is 1953847 and that of the model PU_W is 2036927.

Figure 4 shows changes in the ratio of torque, where the abscissa λ is the tip speed ratio. The torque T was normalized by the maximum torque T_{ref} at $\lambda = 6.4$ giving the maximum power coefficient C_p in case PU_O. Furthermore, Fig. 5 is the ratio of power coefficient C_p. The power coefficient C_p was divided by the maximum power coefficient $C_{p\,ref}$ at $\lambda = 6.4$ in case PU_O. As shown in Fig. 5, the numerical simulation result of PU_O is in good agreement with the experimental one although the power coefficient ratio of simulation is slightly high at around $\lambda = 10.2$ of high tip speed ratio. In comparison of simulation results, the power coefficient ratio in case PU_W almost corresponds to the one of PU_O in a range of λ lower than $\lambda = 6.4$ though the ratio of PU_W at $\lambda = 6.4$ is 0.94. Besides, the trends of C_p are based on the torque as shown in Fig. 4.

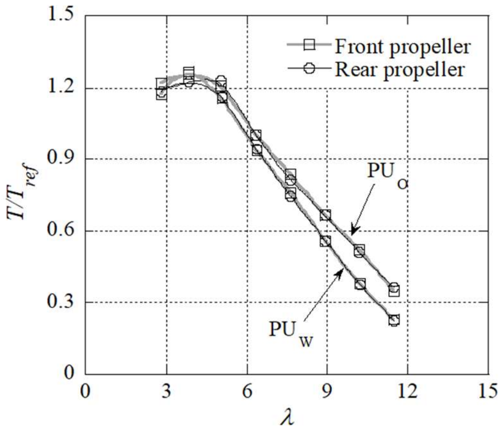


Fig. 4 Changes in torques due to tip speed ratio.

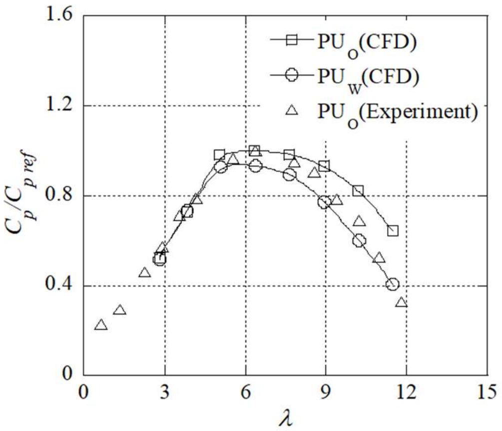


Fig. 5 Changes in ratio of power coefficient.

Figure 6 shows the rear blade load at 90% span location, midspan and 10% span location in case $\lambda = 3.9$. It is noticed that there is little difference in blade load in a range between hub to midspan. On the other hand, it was confirmed that the high blade load can be achieved at 90% span location around the blade tip in case PU_W.

4. Conclusions

In this research, effectiveness of winglets at rear propeller of counter-rotating tidal stream power unit was verified by the circulation type water channel tests. In the experiments, the flow velocity was varied from 0.7 m/s to 0.8 m/s, 0.9 m/s and 1.0 m/s. Besides, the blade performance was analyzed by the CFD. The concluding remarks are as follows.

(1) The tilt angle in case PU_W with winglets is about 8 degrees lower than the case PU_O regardless of the flow velocity.

(2) The counter-rotational speed in case PU_W with winglets became 1.3 times higher than the case PU_O without winglet bases on the lower tilt angle.

(3) The power coefficient ratio in case PU_W almost corresponds to the one of PU_O in a range of tip speed ratio λ lower than $\lambda = 6.4$ though the ratio of PU_W at $\lambda = 6.4$ is 0.94.

(4) At lower tip speed ratio λ, the high blade load can be achieved at 90% span location around the blade tip by setting the winglets.

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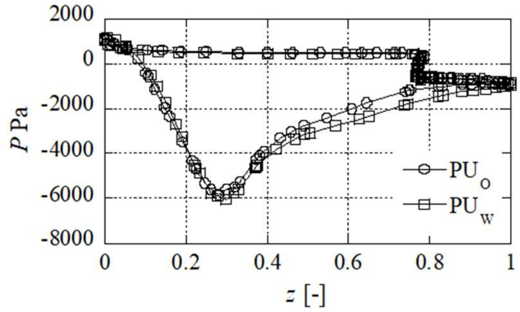
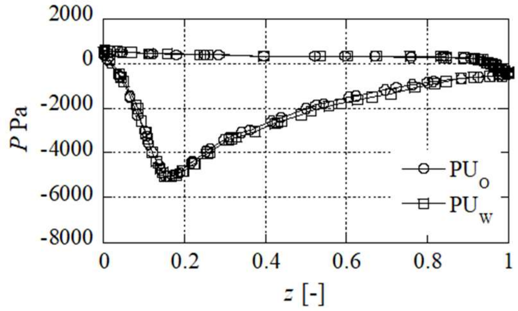
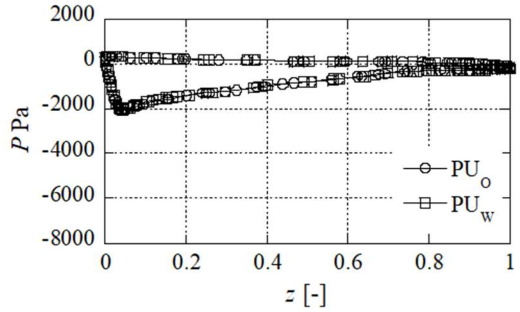


(a) 90% span location.



(b) Midspan.



(c) 10% span location.

Fig. 6 Rear blade load at $\lambda = 3.9$.

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